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Instanton Effects in $N\bar{N}$ Annihilation

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Abstract

It is shown that specific spin-flavour properties of the nonperturbative interaction between quarks induced by instantons allow us to explain the peculiarities of the OZI rule violation in $N\bar{N}$ annihilation. New experiments to test the instanton mechanism of the OZI rule violation are proposed.

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Introduction

Recently, in papers [1] and [2] it has been mentioned that the instanton induced interaction between quarks [3] can give an essential contribution to processes of $N\bar{N}$ annihilation. However, the most fundamental peculiarities of the OZI rule [4] violation in these reactions [5]-[29] have been unanswered.

In this note, a detailed analysis of the available data on the OZI rule violation in $N\bar{N}$ annihilation is made in the framework of the model in which instantons determine spin effects in hadron spectroscopy [30] and hadron reactions at high energies [31]. [2].

This model was suggested several years ago and was very successful in the description of hadron properties. It was shown [30] that specific spin-flavour properties of instanton-induced interaction between quarks lead to essential violation of the OZI rule in the meson pseudoscalar nonet. At the same time, because the interaction of that kind is absent in the vector nonet, this fact explains the $\omega - \Phi$ mixing angle an being small [32], [33]. Later, this model was successfully applied to resolve the so called "spin crisis" [34] connected with the anomalous contribution of strange quarks to the proton spin and also to explain the anomalous Gottfried sum rule violation [35] caused by the violation of the $SU(2)_f$-flavour symmetries of the nucleon quark sea [36].

Achievements of the instanton mechanism in explanations of the pecularities of the OZI rule violation in meson spectroscopy and deep-inelastic scattering give us serious arguments for the assumption that just this mechanism is responsible for the violation of the OZI rule in $N\bar{N}$ annihilation.

Instanton Mechanism for OZI rule violation in $N\bar{N}$ annihilation

The value of the OZI rule violation is determined by the ratio of the matrix-elements [37]:

$$Z = \frac{M(A+B\to \bar{s}s+X)}{[M(A+B\to \bar{u}u+X)+M(A+B\to \bar{d}d+X)]/\sqrt{2}}. \qquad (1)$$

From this one can get the following form for the cross section ratio:

$$R = \frac{\sigma(A+B\to\phi X)}{\sigma(A+B\to\omega X)} = (\frac{Z+\tan\delta}{1-Z\tan\delta})\cdot f, \qquad (2)$$

where $\delta = \Theta - \Theta_i$ is the deviation from the ideal mixing angle $\Theta_i = 35.3^0$ in the vector nonet ($\Theta = 39^0$ follows from the quadratic Gell-Mann-Okubo mass formula and $\Theta = 36^0$ comes from the linear formula) and f is a phase space factor.

In Table 1 (see [37]) the experimental data on the OZI violation for different final hadronic states recently obtained in the $N\bar{N}$ annihilation at rest are presented [5]-[16]. The main conclusion which can be made from the analysis of these data is the value of the OZI violation is extremely sensitive to values of the spin of initial and final particles. So, the most remarkable fact is that the large violation comes only from the S-wave state of initial nucleons. At the same time the violation in the P-wave state is small. This fact is very difficult to explain in the framework of the conventional mechanism of the OZI violation through the $K-$mesons rescattering in the intermediate state [38] (see the discussion in [37]).

It also follows from Table 1 that the value of the violation is very sensitive to quantum numbers of final particles. So, the essential violation is observed in the reactions $N\bar{N}\to\Phi\gamma$ and $N\bar{N}\to\Phi\pi$. At the same time the violation in the reactions $N\bar{N}\to\Phi\rho$, $N\bar{N}\to\Phi\pi\pi$, and $N\bar{N}\to\Phi\eta$ is almost absent.

[2] For introduction to instanton effects in spin physics see review [31] and references therein.

A strong dependence on the spin and flavour of interacting particles is a fundamental peculiarity of the quarks interaction induced by instantons [3], [39] [3]:

$$\begin{aligned}\mathcal{L}_{eff}^{(N_f=3)} &= \int d\rho n(\rho)\Big\{\prod_{i=u,d,s}(m_i\rho-\frac{4\pi}{3}\rho^3\bar{q}_{iR}q_{iL})+\\ &\frac{3}{32}(\frac{4}{3}\pi^2\rho^3)^2[(j_u^a j_d^a-\frac{3}{4}j_{u\mu\nu}^a j_{d\mu\nu}^a)(m_s\rho-\frac{4}{3}\pi^2\rho^3\bar{q}_{sR}q_{sL})+\\ &\frac{9}{40}(\frac{4}{3}\pi^2\rho^3)^2 d^{abc}j_{u\mu\nu}^a j_{d\mu\nu}j_s^c+2perm.]+\frac{9}{320}(\frac{4}{3}\pi^2\rho^3)^3 d^{abc}j_u^a j_d^b j_s^c+\\ &\frac{igf^{abc}}{256}(\frac{4}{3}\pi^2\rho^3)^3 j_{u\mu\nu}^a j_{d\nu\lambda}^b j_{s\lambda\mu}^c+(R\longleftrightarrow L)\Big\}\,,\end{aligned} \tag{3}$$

where $q_{R,L}=\frac{(1\pm\gamma_5)}{2}q(x)$, $j_i^a=\bar{q}_{iR}\lambda^a q_{iL}$, $j_{i\mu\nu}^a=\bar{q}_{iR}\sigma_{\mu\nu}\lambda^a q_{iL}$, and $n(\rho)$ is the instanton density. Neglecting quark masses and using the Fierz transformation one can transform (3) to the following flavour determinant:

$$\begin{aligned}\mathcal{L}_{eff}^{(N_f=3)} \sim \varepsilon^{ijk}\varepsilon_{i'j'k'}\times\Big[&\left(\bar{q}_{Ri_1}q_L^{i'}\right)\left(\bar{q}_{Rj}q_L^{j'}\right)\left(\bar{q}_{Rk}q_L^{k'}\right)+\\ &+\frac{3}{8(N_c+2)}\left(\bar{q}_{Ri}q_L^{i'}\right)\left(\bar{q}_{Rj}\sigma_{\mu\nu}q_L^{j'}\right)\left(\bar{q}_{Rk}\sigma_{\mu\nu}q_L^{k'}\right)\Big]\end{aligned} \tag{4}$$

One can emphasize three the most remarkable characteristics of this interaction. First, it contributes only to the $S-$ wave scattering of initial particles. This property comes from $O(4)$ symmetry of the instanton solution [41], which leads to the point-like behavior of the quarks scattering amplitude off instanton (see for example [42]).

Second, helicities of incoming and outcoming quarks from instanton (antiinstanton) are strongly correlated: all incoming quarks are left (right), all outcoming quarks are right (left). Specific helicity properties of the t'Hooft's interaction (3) are determined by the helicity structure of the zero fermion modes in the instanton field which give the dominated contribution to the instanton induced quark scattering amplitude.

The most outstanding consequence of this structure is a very large violation of the quark helicities in the instanton field:

$$\Delta Q_5 = -2N_f. \tag{5}$$

This fact provides the basis for explanation of the "spin crisis" in the framework of the instanton mechanism (see a discussion in [31]). It should be mentioned also that just this property of the quark and lepton interaction off the electroweak instantons violates the baryon number conservation [3]. At present, the possibility of its anomalous violation due to a multiple creation of the gauge bosons from the instanton vertex at high energies is widely discussed (see [42] and references therein).

The third property of the instanton Lagrangians (3), which has a direct relation to the OZI rule violation is that it is not equal to zero only for different flavours of the interacting quarks. Just this peculiarity of the Lagrangian (3) enhances the probability of transitions between different quark flavours and determines the mixing angles of the $SU(3)_f$-multiplets [30].

On the whole, all these peculiarities are just the reason for splitting of masses between hadron multiplets ($\pi-\rho, N-\Delta, \eta-\eta'$ and so on). At the same time, the absence of the P-wave instanton-induced quark interaction leads to the small spin-orbital splitting in the hadron excited states [30]. It provides a solution of the old problem of hadron spectroscopy connected with the

[3] The Lagrangian (3) was obtained under the assumption $p\rho \ll 1$, where p is the characteristic momentum of quarks. Taking into account the inequality of $p\neq 0$ one obtains some form factor in (3) which depends on the virtualities of quarks [40].

observed small spin-orbital splitting. So, many models which take into account only a long-range gluon exchange contribution to the spin-spin quark interaction, give also a very large spin-orbital splitting which contradicts the experimental data [43].

Let us consider now instanton effects in the $\bar{N}N$ annihilation. We will suppose that just instantons lead to a large violation of the OZI rule in these reactions. Other mechanisms of this violation, from our point of view, can be either annihilation through perturbative gluons or rescattering [38]. However, it was shown in papers [32], [33] that the gluon perturbative exchange leads to mixing angles in the pseudoscalar nonet to one order of magnitude smaller than instanton exchange. Moreover, this mechanism predicts the wrong sign of the $\omega - \Phi$-mixing [32]. The second mechanism, probably, is also negligible when one takes into account the form factors in the K-meson-nucleon interaction vertex [44] [4].

Recently, the conception of the "internal polarized strange sea" (IPSS) was proposed [37]. Although the fundamental mechanism which could lead to this phenomenon was not explained in [37], this hypothesis is supported by the result of measurements of the part of the proton spin carried by the strange quarks by the EMC, SMC, E-142, E-143 Collaborations [34]. We will compare the predictions of the IPSS model with predictions of the instanton model under discussion.

By using the specific properties of the instanton-induced Lagrangians (3), (4), one can formulate some selection rules in order to predict the values of the OZI rule violation in different channels.

First of all, it is expected that a large OZI rule violation takes place only in the S- wave initial states, because the interaction (3) is not equal to zero for the S-wave quark-quark interactions. This rule is well fulfilled for all channels where we have experimental data for different relative weights of the $S-$ and $P-$ waves in the initial nucleon state (see Table 1). It should be pointed out that just the absence of the $P-$ wave interaction induced by the instanton explains observed smallness of the spin-orbital splitting in hadron excited states [30].

The second selection rule follows from the spin structure of different terms in (4). So, the largest violations in that kind of reactions, to which the first term in (4) does contribute, are expected. One can easy understand that this term corresponds to the total initial quark spin $S_{q\bar{q}} = 0$, and therefore the OZI rule violation has the maximum magnitude for reactions with $S_{N\bar{N}} = 0$. This effect is actually observed in the reaction $\bar{N}N \to \Phi\gamma$. In hadron spectroscopy, the same effect leads to a very large contribution of the instanton induced interaction to the masses of particles from the pseudoscalar nonet and to the dominance of the scalar diquark in the nucleon wave function [30]. From this rule it follows that the value of the violation of the OZI rule in the reaction $\bar{N}N \to \Phi\pi$ should be smaller. This reaction originates through the $^3S_1$ state of two nucleons, and therefore only the second term in (4), suppressed as $1/N_c$, gives a nonzero contribution. The dominance of the $^3S_1$ state in the reaction leads to the specific angular dependence of the $K-$mesons from $\Phi-$decay

$$W(\Theta) \approx 1 - cos^2(\Theta). \tag{6}$$

This dependence has been observed in the experiment [46].

It should be emphasized that we do not expect a significant violation of the OZI rule in the production of the tenzor 2^{++} mesons because the instanton vertex (4) does not include the term with appropriate quantum numbers.

Further, the third selection rule results from a suppression of the direct creation of the vector mesons in the instanton field. This suppression comes from specific helicity properties of the quark zero modes. So, for quark on zero mode the following condition should be satisfied [3]:

$$\vec{\sigma}_q \oplus \vec{c}_q = 0, \tag{7}$$

[4] In paper [45] it was shown that the K-meson contribution to the nucleon strange sea should be very small when one takes into account form factors in the meson-nucleon vertex.

where $\vec{\sigma}_q$ is a spin and $\vec{c}_q$ is a colour spin for the $SU(2)_c$ subgroup of the $SU(3)_c$-colour group. From relation (7) and from the fact that quarks outcoming from the instanton should have the same helicities, it immediately follows that without spin-flip the instanton production of the colourless vector mesons is forbidden. In the one-instanton approximation, the quark spin-flip can be induced only by the current quark masses. Therefore, the production of the vector mesons which consist of the light u- and d-quarks should be small. Just this property leads to a very small OZI rule violation in the reactions $\bar{N}N \to \Phi\rho$, $\bar{N}N \to \Phi\omega$. In the quark model [30] it results in the smallness of the $\Phi - \omega$-mixing angle.
The forth selection rule is connected with the flavour structure of the Lagrangians (3), (4). So, it is not equal to zero only for different quark flavours. Therefore, the violation of the OZI rule in the reactions, where the final hadrons include the same kind of quarks, for example in reactions $\bar{N}N \to \Phi 2\pi$ and $\bar{N}N \to \Phi\Phi$, should be suppressed by the parameter of the instanton density in the QCD vacuum [33]:

$$f = \pi^2 \rho^4 n_I \approx \frac{1}{20}. \tag{8}$$

This rule also decreases the OZI rule violation in the reactions $\bar{N}N \to \Phi\eta$ and $\bar{N}N \to \Phi\eta'$ because the wave functions of η and η'-mesons include some part of the strange quarks. However, in this case, this explanation is not enough because the mesons can be created through their nonstrange isospin singlet component [5]. From our point of view, the suppression of the yield of the η and η'-mesons in the reactions $\bar{N}N \to \Phi\eta$ and $\bar{N}N \to \Phi\eta'$ is directly related to the "spin crisis" [34]. In papers [47] it was shown that the EMC result, can be understood as decoupling of the isosinglet η'_0 from the nucleon. In the framework of the instanton model, the decoupling of the isosinglet meson comes from the fact that the instanton-induced interaction (3) violates the $U_A(1)$-symmetry in QCD. So, the instanton-induced interaction is repulsive in the isosinglet channel [30], [33], [48]. Without taking into account the octet-singlet mixing, it leads to the unbound η'_o-meson state [48], and therefore its interaction with the nucleon should be very small.
The fifth rule comes from the helicity properties of the instanton vertex. So, in the c.m. frame, all quarks incoming into the instanton should have the same helicity. It leads to the enhancement of the OZI sum rule violation from the $S^Z_{\bar{N}N} = 0$ two-nucleon state, where $S^Z_{\bar{N}N}$ is the projection of the total spin of the $\bar{N}N$ pair on the direction of their relative motion.
Thus, some rules, which come from the specific properties of the instanton-induced interaction between quarks, have been formulated here.
These rules are well satisfied for the available data on $\bar{N}N$-annihilation at rest (see Table 1). However, there are the data on the OZI rule violation in flight experiments [17]-[27]. One of the most remarkable peculiarities of these data is a very fast decrease of the violation with growing energy. In the framework of the instanton model this effect can be explained easily. The instanton is a quasiclassical object, extended in the space-time and therefore all quarks, which interact with instanton should have sufficiently small momenta to provide a large value for the interaction amplitude. It means that the momenta of the quarks should obey the condition $| \vec{p} | \leq 1/\rho_c$, where $\rho_c \approx 1.6\ GeV^{-1}$ is the average instanton size in QCD vacuum [33], and therefore the instanton effects are large only near the thresholds [6].
The instanton model also predicts a strong dependence of relative values of the OZI rule violation as a function of the momentum transfer. So, the average size of the instanton $\rho_c \approx 1.6\ GeV^{-1}$, determining the momentum transfer dependence for the reactions with OZI

[5] The author is grateful to S.B. Gerasimov for useful discussions of this problem.

[6] It should be mentioned that, probably, the anomalous violation of the OZI rule is possible also at high energies, but only in events with a large multiplicity. In these events, large initial energy transforms to the creation of a large number of gluons ($N \sim 1/\alpha_s$) with small energies ($E \sim 1/\rho_c$). This fact provides the anomalous behavior of the spin-dependent structure function $g_1(x)$ at small x in QCD and the possibility of the anomalous violation of the baryon number conservation in the electroweak theory (see a discussion in [49]).

violation significantly differs from the confinement size $R_{conf} \approx 5GeV^{-1}$, which determines the momentum transfer dependence of the processes without OZI rule violation. As a result, we should have a strong momentum transfer dependence of the ratio of the cross-sections of these reactions. This effect is obvious in different reactions (see the discussion in [37]) and one cannot find its appropriate explanation in the framework of the convenient models.

Another challenging problem for the $\bar{N}N$ annihilation models is the backward peak in the reaction $\bar{P}P \rightarrow K^+K^-$ [50]. In our model this phenomenon can be explained by a large changing of the helicities ($\Delta\lambda = -6$) induced by the instanton. So, every quark spin-flip leads to the factor

$$M \sim \bar{q}_R q_L \sim sin(\frac{\Theta}{2}) \tag{9}$$

in the matrix element of the reaction. Therefore, one can estimate that the spin-flip leads to the following angular dependence of the cross-section:

$$\frac{d\sigma^{\bar{P}P \rightarrow K^+K^-}}{d\Omega} \sim sin^6(\frac{\Theta}{2}). \tag{10}$$

Thus, the instanton induced-interaction allows us to describe, at least qualitatively, principal peculiarities of the OZI rule violation in $\bar{N}N$-annihilation.

Possible Tests of the Model

A very important task is to perform the experiments, which would give a direct indication of the instanton mechanism of the $\bar{N}N$-annihilation. One of these important experiments is a measurement of the cross section of the reaction $\bar{N}N \rightarrow \Phi\gamma$ on a gas target. This experiment will test the domination of the $S-$wave mechanism of the OZI rule violation. So, we predict a sharp decrease of the ratio $(\Phi\gamma/\omega\gamma)$ on a gas target, where the annihilation dominates in the $P-$wave state in comparison with the result in a liquid [6], where the annihilation dominates in the $S-$wave state. It should be mentioned that the IPSS model [37] predicts a sharp increase of the ratio, and therefore this experiment will allow unambiguous conclusion about the reliability of one of these models.

Another experiment could be a measurement of the spin correlations in the reaction [37]:

$$\bar{P} + P \rightarrow K^* + \bar{K}^*. \tag{11}$$

The IPSS model predicts a strong correlation in the final $S_{K^*\bar{K}^*} = 2$ state for this reaction. Our model gives the correlation in the $S_{K^*\bar{K}^*} = 0$ state because the initial state $S_{\bar{p}p} = 0$ dominats.

A possible test for the model is the angular distribution of dileptons in the reaction:

$$p + p \longrightarrow \phi + X, \tag{12}$$

$$\hookrightarrow e^+e^- \tag{13}$$

So, the IPSS model predicts:

$$W(\Theta) \approx 1 + cos^2(\Theta). \tag{14}$$

At the same time, in our model the dependence

$$W(\Theta) \approx 1 - cos^2(\Theta) \tag{15}$$

is expected. This form results from the longitudinal polarization of the Φ- meson. It was mentioned above that the quark-antiquark pair created by the instanton (antinstanton) has the helicity $\lambda = \pm 1$, and it is necessary to flip a helicity of one of the quarks to create a vector meson. As result we have a longitudinal polarization of the created vector mesons.

It would be interesting to measure the dependence

$$R(n) = \frac{\sigma(\bar{N}N \to \Phi(n\pi))}{\sigma(\bar{N}N \to \omega(n\pi))}. \tag{16}$$

It was pointed out above (see also [49], [51]) that the anomalous behavior of the spin-dependent structure function $g_1(x)$ [34] at low x is due to the increase of the number of gluons from the instanton vertex created together with a pair of strange and nonstrange quarks. It could be shown that the yield of an even number of the gluons from the instanton vertex is enhanced (see estimations in [52]) and therefore after hadronization of these gluons to the pions one can expect the oscillator-like behavior of the function $R(n)$ with maxima at odd numbers of the pions.

From our point of view, the most direct experiments to check the instanton model are experiments on measurement of the OZI rule violation with polarized beams. One of these processes could be the reaction

$$\vec{P} + \vec{P} \to P + P + \Phi. \tag{17}$$

Taking into account the fact that the instanton-induced interaction (3) is the $S-$wave interaction, we expect the enhancement of production of Φ in the $S_{PP} = 0$ state and, respectively, the following value of two-spin asymmetry in this reaction at rest:

$$A = \frac{Y_\Phi(\uparrow\uparrow) - Y_\Phi(\uparrow\downarrow)}{Y_\Phi(\uparrow\uparrow) + Y_\Phi(\uparrow\downarrow)} \approx -1. \tag{18}$$

This experiment is planned [53], and its realization would be very interesting.

Conclusion

The complex structure of the QCD vacuum caused by of the strong nonperturbative fluctuations of the gluon fields - instantons in the QCD vacuum manifests nontrivially in $\bar{N}N$- annihilation. In this note, we have argued that the unique spin-flavour properties of the instanton-induced interaction between quarks allow us to explain the peculiarities of the OZI rule violation in these reactions.

Further experimental and theoretical investigation of the instanton effects in the OZI rule violation is very important to shed light on the role of the fundamental structure of the QCD vacuum in $\bar{N}N$-annihilation.

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TABLE 1. The ratios $R = \phi X/\omega X$ for production of the ϕ and ω - mesons in antinucleon annihilation at rest. The data are given for annihilation in liquid hydrogen target (percentage of annihilation from P-wave is $\sim 10-20\%$), gas target (~61% P-wave) and LX-trigger [5] (~86-91% P-wave).

Final state	Initial states	B.R.$\cdot 10^4$	$R \cdot 10^3$	$\|Z\|$ (%)	Comments
$\phi\gamma$	$^1S_0, ^3P_J$	0.17 ± 0.04	250 ± 89	42 ± 8	liquid,[6]
$\phi\pi^0$	$^3S_1, ^1P_1$	5.5 ± 0.7	96 ± 15	24 ± 2	liquid,[6]
$\phi\pi^0$		1.9 ± 0.5			gas, [5]
$\phi\pi^0$		0.3 ± 0.3			LX-trigger, [5]
$\phi\pi^-$	$^3S_1, ^1P_1$	9.0 ± 1.1	83 ± 25	22 ± 4	liquid,[9]-[12]
$\phi\pi^-$		14.8 ± 1.1	133 ± 26	29 ± 3	$\bar{p}d, p < 200\ MeV/c$, [7]
$\phi\pi^-$			113 ± 30	27 ± 4	$\bar{p}d, p > 400\ MeV/c$, [7]
$\phi\pi^+$			110 ± 15	26 ± 2	$\bar{n}p$, [7]
$\phi\eta$	$^3S_1, ^1P_1$	0.9 ± 0.3	6.0 ± 2.0	1.3 ± 1.2	liquid,[6]
$\phi\eta$		0.37 ± 0.09			gas, [5]
$\phi\eta$		0.41 ± 0.16			LX-trigger, [5]
$\phi\rho$	$^1S_0, ^3P_J$	3.4 ± 0.8	6.3 ± 1.6	1.4 ± 1.0	gas, [5],[15]
$\phi\rho$		4.4 ± 1.2	7.5 ± 2.4	2.1 ± 1.2	LX-trigger, [5],[15]
$\phi\omega$	$^1S_0, ^3P_{0,2}$	6.3 ± 2.3	19 ± 7	7 ± 4	liquid, [14],[16]
$\phi\omega$		3.0 ± 1.1			gas, [5]
$\phi\omega$		4.2 ± 1.4			LX-trigger, [5]
$\phi\pi^0\pi^0$	$^{1,3}S_{0,1}, ^{1,3}P_J$	1.2 ± 0.6	6.0 ± 3.0	1.3 ± 2.0	liquid,[6]
$\phi\pi^-\pi^+$		4.6 ± 0.9	7.0 ± 1.4	1.9 ± 0.8	liquid,[13]
$\phi X, X = \pi^+\pi^-, \rho$		5.4 ± 1.0	7.9 ± 1.7	2.4 ± 1.0	gas, [5],[15]
$\phi X, X = \pi^+\pi^-, \rho$		7.7 ± 1.7	11.0 ± 3.0	4.0 ± 1.4	LX-trigger, [5],[15]